Shielding Design of RIKEN RI Beam Factory

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Abstract

The construction of the RIEKN RI Beam Factory has started and will be finished by the end of March 2003. It plans to accelerate all the ions from hydrogen to uranium with the intensity of 1 pμA. Its maximum beam energy is 400 MeV/nucleon for light ions (A<40) and 150 MeV/nucleon for uranium. Since the RI Beam Factory will produce such high-intensity heavy-ion beams, radiation shielding is a serious problem. We report here the shielding design of the RI Beam Factory giving emphasis to prescription for dose estimation.

1 RI Beam Factory

The RIKEN RI Beam Factory (RIBF) aims to produce the world's most intense RI beams at energies of several hundreds of MeV/nucleon over the whole range of atomic masses [1]. To this end, two cyclotrons will be constructed as post-accelerators of the existing RIKEN Ring Cyclotron (RRC). One is the K930-MeV Intermediate-stage Ring Cyclotron (IRC) and the other is the K2500-MeV Superconducting Ring Cyclotron (SRC). This series of cyclotrons is capable of accelerating light ions (A<40) up to 400 MeV/nucleon and very heavy ions more than 100 MeV/nucleon with the beam intensity of 1 pμA. The accelerated beams will be used to produce RI beams via projectile-fragment reaction. The RI-beam production will be done at a new projectile-fragment separator (Big-RIPS). RI beams produced at the Big-RIPS will be guided to experimental halls to perform various experiments.

2 Shielding Calculation

We will hereafter concentrate on the radiation shielding of the SRC and the Big-RIPS because the maximum beam energy is 127 MeV/nucleon for the IRC, which is nearly same as the existing RRC. To make reliable estimation of radiation dose, we used neutron production data as a source term of shielding calculations. We calculated the dose attenuation in shielding material and compared the results with shielding experiments.

2.1 High-energy Neutron Production by Heavy Ions

Recent vigorous measurements of neutron production in heavy-ion reactions [2-3] gave us a firm basis of shielding calculation. Fig. 1 shows an example, the thick-target yield of neutrons by a 400-MeV/nucleon ^{20}Ne beam. We used the data shown in Fig.1 as a source term of shielding calculation. As we will discuss later, a 400-MeV/nucleon ^{20}Ne beam is not the most serious beam in radiation shielding of the RIBF. We introduce a simple scaling law to apply the present data to other cases.

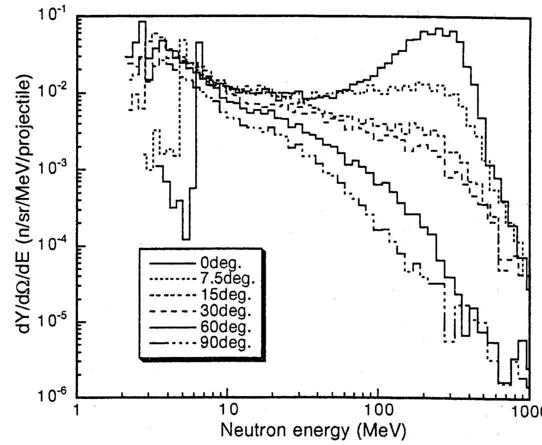

Fig.1 Double-differential neutron yields at a thick Cu target bombarded by a 400-MeV/nucleon ^{20}Ne beam

2.2 Deep Penetration of High-energy Neutrons

The next step is to evaluate attenuation of the neutron dose. To this end, we calculated deep penetration of neutrons using the ANISN code [4]. The cross-section data set used here is the DLC-119/HIRO86R group constant [5]. Fig.2 illustrates attenuation of effective dose in shielding materials that are made of normal concrete slab and iron slab. Note that the neutron fluence calculated by the ANISN was converted to the effective dose using the ICRP-74 conversion factors.

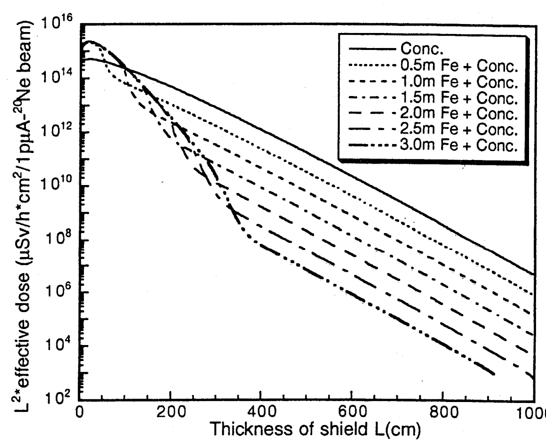

Fig.2 Deep penetration of neutrons in shielding materials. The 0-degree data in Fig. 1 are used as a source term of shielding calculation.

Beyond the neutron build-up region, effective dose (H) obeys the simple exponential law as follows,

$$H=h_0(\theta)e^{-t/\lambda}/L^2.$$

Here, L is the distance from a source; t is the thickness of shield and λ is the dose attenuation length. The h_0 parameter depends on θ, the angle between a beam axis and emitted neutrons. The attenuation length λ also depends on the angle θ, but it ranged from 48.1 cm to 49.1 cm for all data shown in Fig. 1. This fact enables us to use the constant value (49 cm) for λ. In addition, dose attenuation in iron is 2.5 times faster than in normal concrete if there is at least 1.0-m thick normal concrete behind iron.

2.3 Comparison with Shielding Experiments

In order to check the dose attenuation calculated by the ANISN, we compared the present estimation with shielding experiments [6-7]. We employed neutron production data by a 400-MeV/nucleon ^{12}C beam [3] in the present comparison because the experiments were performed with 400-MeV/nucleon ^{12}C beams. We summarize the results in Table 1. The present calculation reproduces well the experiments except for the 0-degree direction. The discrepancy for forward shielding should be resolved in the future. In the last column, we also calculated effective dose with somewhat larger attenuation length (λ = 53 cm). In this case, the calculated value is at least 2 times larger than the observed value. We use the λ value of 53 cm for actual shielding design taking into account experimental errors.

Table1 Comparison of shielding calculation with experiments. Beam intensity is 3×10^8 pps except for the first two data (1×10^8 pps). The unit of effective dose is μSv/h. (* 380-cm thick normal concrete + 50-cm thick iron)

L(m)	t(cm)	θ(deg.)	Obs.	Calc.	λ=53cm
5.0	280	0.00	66	498	767
10.0	505*	0.00	1.5	1.26	2.75
13.86	286	13.38	16.8	24.9	38.7
12.98	268	21.48	13.9	19.7	29.8
12.38	256	30.56	6.5	13.6	20.1
12.12	250	40.29	3.15	5.66	8.32
12.40	256	54.94	0.75	1.02	1.52

2.4 Mass and Energy Dependence

Since the RIBF plans to accelerate all the elements up to uranium, we should know which beam produces the largest amount of radiation.

Table 2 Relative value of effective dose in the RIBF

ion	Beam energy (MeV/nucleon)	Intensity (pμA)	Relative dose
$^{16}O^{7+}$	400	1	0.80
$^{20}Ne^{10+}$	400	1	1.00
$^{40}Ar^{17+}$	400	1	2.00
$^{84}Kr^{30+}$	300	1	2.36
$^{129}Xe^{38+}$	200	1	1.61
$^{238}U^{49+}$	100	1	0.74
$^{238}U^{58+}$	150	0.2	0.33

We assumed that effective dose originated from a heavy-ion beam was proportional to the ion mass and the square of the ion energy per nucleon. To verify this simple scaling law, we made dose calculations with neutron production data by 400-MeV/nucleon ^{12}C, ^{56}Fe and a 180-MeV/nucleon ^{12}C beam [3]. The result is that the effective dose obtained from the scaling law always lies in the safety side if we use 400-MeV/nucleon ^{20}Ne data as a source term of shielding calculation. From this investigation, we predicted in Table 2 the amount of radiation for various beams produced in the RIBF. A 300-MeV/nucleon ^{84}Kr beam gives the largest amount of radiation. The scaling factor of 2.36 is introduced for the ^{20}Ne data.

3 Dose Limit Criteria

We explain here the dose limit criteria of the RIBF. The dose limit criteria was determined to meet the ICRP-60 recommendation as shown in Table 3. The value for the site boundary is an engagement with the local government.

Table 3 Criteria of effective dose for the RIBF

Item(boundary)	Dose limit
Non-restricted area in radiation controlled area	25 μSv/h (1 mSv/w)
Radiation controlled area	2.6 μSv/h (1.3 mSv/3m)
Office in site	0.5 μSv/h (250 mSv/3m)
Site boundary	50 μSv/y

4 Shielding of SRC

We applied the methods mentioned above for the radiation shielding of the SRC. The beam loss is assumed to be point-like and its maximum value is 10 pnA for injection and extraction, respectively. The beam loss will be kept less than 10 pnA by radiation and/or beam-loss monitoring. Fig. 3 shows the prediction of the effective dose on the roof of the SRC room. In the present calculation, the roof is 3m-thick normal concrete and the 3-m thick local shield of normal concrete is added to suppress the radiation produced in extraction.

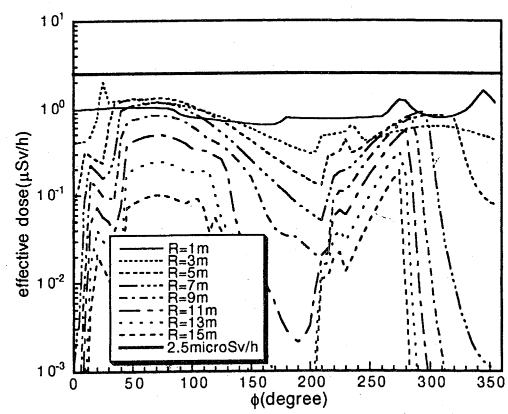

Fig.3 Effective dose distribution on the SRC roof. The position on the roof is given by the polar coordinates R and φ. The origin is just above the machine center of the SRC. At the extraction point, the beam direction is the 150-degrees direction.

5 Shielding of Big-RIPS

The Big-RIPS needs very thick shield because a 1-pμA primary beam stops at the target and the analysing magnet. It is necessary to contain the Big-RIPS in tunnel-like local shield. Local shield is usually placed close to a radiation source. This implies that fast neutrons emitted from the source inject into shielding material with a large injection angle, especially in the forward direction. Note that the injection angle (α) defined here is an angle from the normal of a shielding wall. Assuming that a path of neutrons across the shield is straight, the shielding thickness increases effectively by a factor of $1/\cos\alpha$. It holds for neutrons with a small injection angle. On the contrary, the effective thickness of shield cannot be determined by the simple geometric consideration for neutrons with a large injection angle, because injected neutrons scatter many times in the shield and diffuse in direction. Hence, we calculated the dose attenuation of slantwise-injected neutrons using the HETC-3step code [8]. The dose attenuation is slower than the $1/\cos\alpha$ correction for $\alpha > 30$ degrees as shown in Fig. 4.

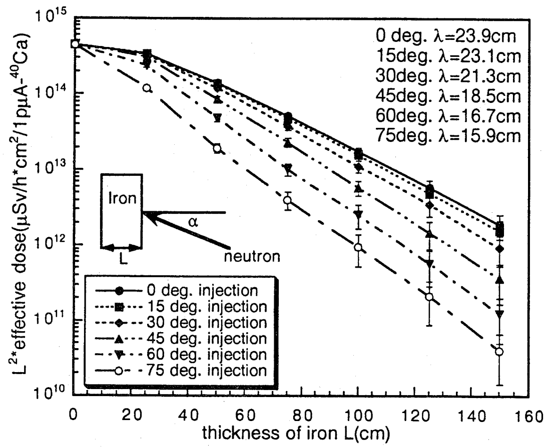

Fig.4 Dose attenuation of slantwise-injected neutrons.

We also calculated effects of back-scattered neutrons from a shielding wall. The back-scattered neutrons are main radiation in the downstream of the second bending magnet of the Big-RIPS, because the direct neutrons from the source are missing in this region. Results are summarised in Fig. 5 where the angular differential albedo function is given as a function of the injection angle of neutrons.

Using these results, we made shielding design of the Big-RIPS. The assumed beam loss is 20 % at the target, 100 % at the first bending magnet and 1.6 % at the first focusing point (F1) where selection of RI beams are performed. The present assumption is a simplified model of the actual complicated situation. Further investigations are necessary which include realistic simulation of the beam loss in the Big-RIPS. We show results in Fig. 6, in which the dose limit is 25 µSv/h at the outer surface of the room. In the present design, the thick iron shield near the second dipole magnet and two sets of triplet Q-magnets (TQ1, TQ2) work as a neutron collimator of 400 mm-ϕ. In this case, thin iron shield is sufficient below the second dipole magnet.

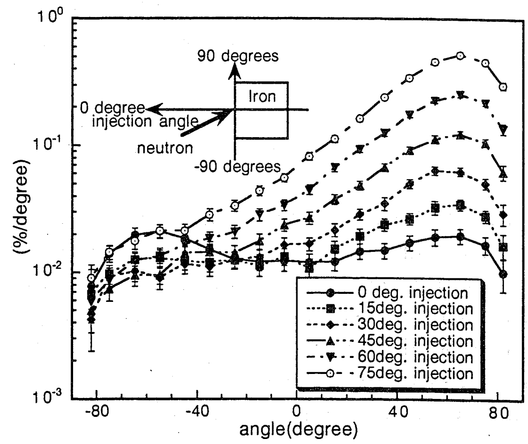

Fig.5 Angular differential effective-dose albedo function.

Reference

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[2] T. Kurosawa et al., "Measurements of Secondary Neutrons Produced from Thick Targets bombarded by High-energy Ne Ions", J. Nucl. Sci. Technol., **36**, 1(1999).

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[4] W. W. Engle, Jr., "A User's Manual for ANISN, A One Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering", K-1963, Oak Ridge Gaseous Diffusion Plant, Oak Ridge (1967).

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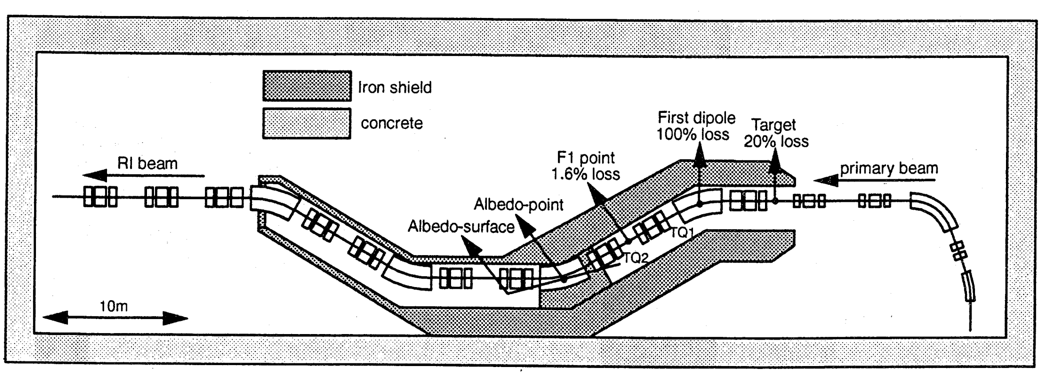

Fig.6 Plane figure of the radiation shield for the Big-RIPS. We assume that albedo neutrons are produced at the "albedo-point". The "albedo-surface" determines the injection and scattering angles of neutrons.